In-Flight Vicarious Calibration of High Spatial Resolution Remote Sensing Systems Using Specular Reflectors

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Outline

- Vicarious Calibration: A New Approach
- SPARC Method: A Unified Spatial and Radiometric Calibration Approach
- Spherical Mirrors as Radiometric Targets
- SPARC Design: Simplified Ground Truth Collection and Radiative Transfer Calculations
- Validation: SPARC applied to IKONOS

A new Approach to Absolute Vicarious Calibration Using Spherical Reflectors

- Combines reflectance-based vicarious approach with stellar calibration
- Accomplished by creating an array of "solar stars" on the ground with convex spherical mirrors
- Each have well characterized radiometric properties and solar like spectra
- Targets are low cost, small and easy to deploy

Previous Application of Convex Mirrors at South Dakota State University (SDSU)

- Used a grid of spherical reflectors to create points source images at different pixel phasing to oversample the sensor Point Spread Function (PSF)

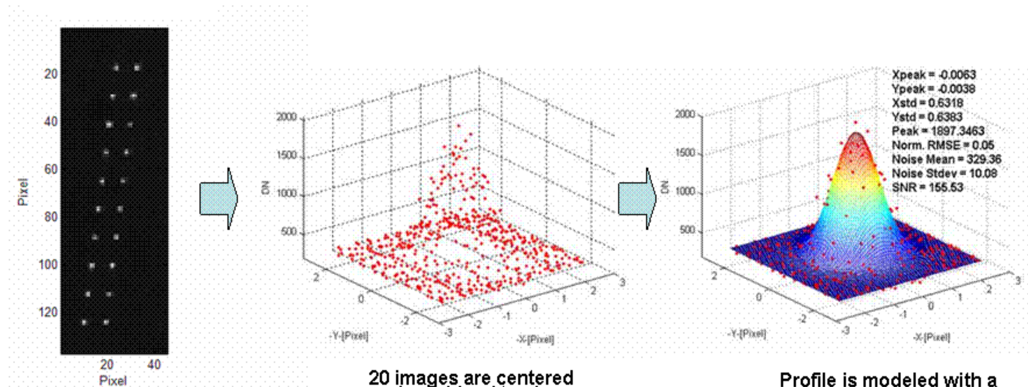


Image of specular mirror array

20 images are centered and combined to give oversampled PSF

Profile is modeled with a Gaussian function

- Purpose was for spatial analysis not radiometry

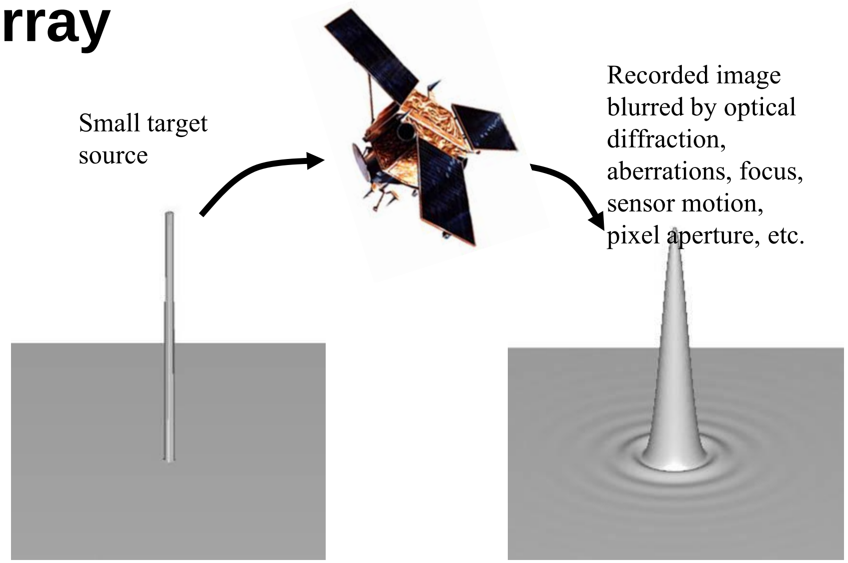
SPecular Array Radiometric Calibration (SPARC) Method

US Patent Application No. 20100032557

Consists of two mirror arrays for spatial and radiometric calibration.

Spatial Array

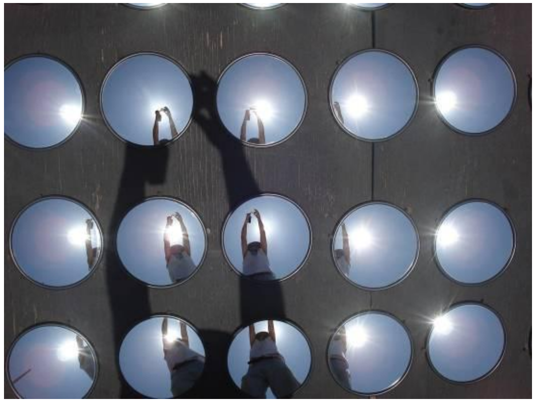
- Produces an oversampled estimate of the sensor point-spread-function (PSF)
- Modified version of SDSU method
- Purpose is to validate the PSF profile and provide knowledge of the ensquared energy when integrating image digital numbers (DN) within a limited spatial window around a small target
- Method takes advantage of the fact that all the energy originating from a subpixel target is contained in the volume of the PSF profile.

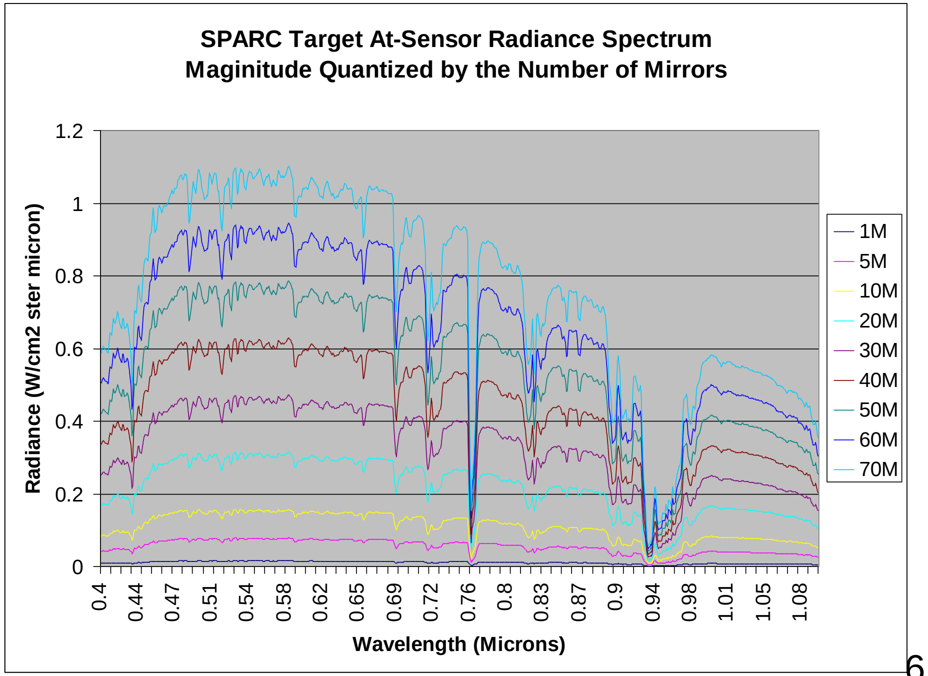


Radiometric Array

SPecular Array Radiometric Calibration (SPARC) Method

- SPARC uses panels of convex spherical mirrors to create an set of radiometric targets with different at-sensor radiance.
- Individual mirrors produce a virtual image of the sun with an upwelling intensity determined by the mirrors radius of curvature.
- Total intensity of each target is quantized by the number of mirrors.
- Design results in a simplified radiative transfer equation for calculating accurate values of at-sensor radiance.
- Only ground truth data required in the field for the calculation of at-sensor radiance is atmospheric transmittance.
- Reflectors for each target are spread over an area approximately the size of the sensors ground sample distance (GSD) or smaller (can be larger but not necessary).
- Targets are deployed on as dark and uniform a background as possible
- A SPARC array can be deployed in a couple hours





Spherical Mirrors as Radiometric Targets

- Collimated light from the sun is reflected from a spherical surface nearly isotropically across the sky
- In a lossless medium the incident solar irradiance $E_o(\lambda)$ can be shown to produce an upwelling intensity $I(\lambda,\theta)$ by the relation

$$I(\lambda,\theta_i) = \tfrac{1}{4}\rho(\lambda,\theta_i)E_o(\lambda)R^2 = \text{watts/sr}$$

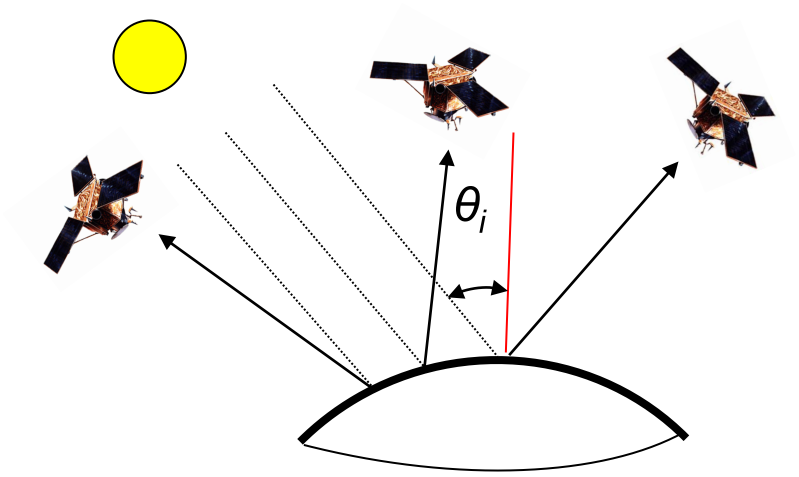
Where,

$\rho(\lambda,\theta_i)$ = Specular reflectance

R = Mirror radius of curvature

θ_i = Angle of incidence (AOI) relative to surface normal

- Variation in upwelling intensity of reflected natural light is typically only a few percent over the hemispherical sky

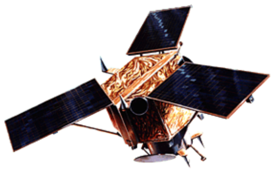


•Bidirectional Reflectance Distribution Function (BRDF) effects are small and accurately characterized in the laboratory

•The are no surface foreshortening effects

•Upwelling intensity is independent of mirror orientation

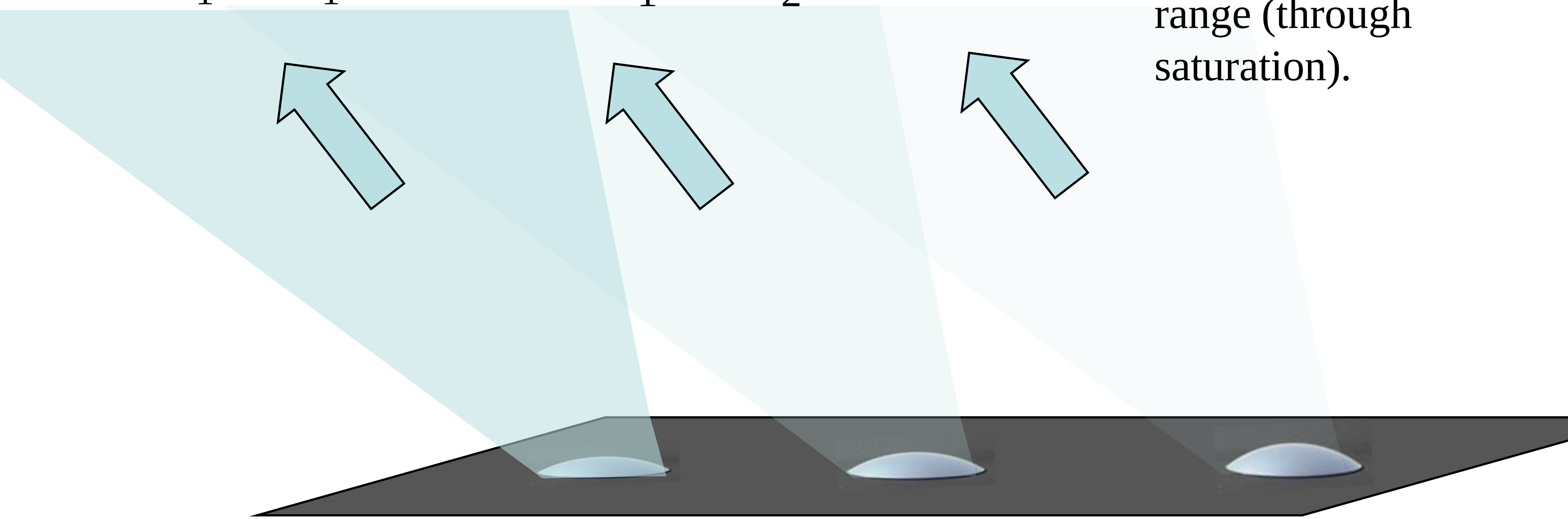
Intensity is controlled accurately by simply changing the radius of curvature



$$I_1 \rangle I_2 \rangle I_3$$

Array can stimulate sensor over the entire dynamic range (through saturation).

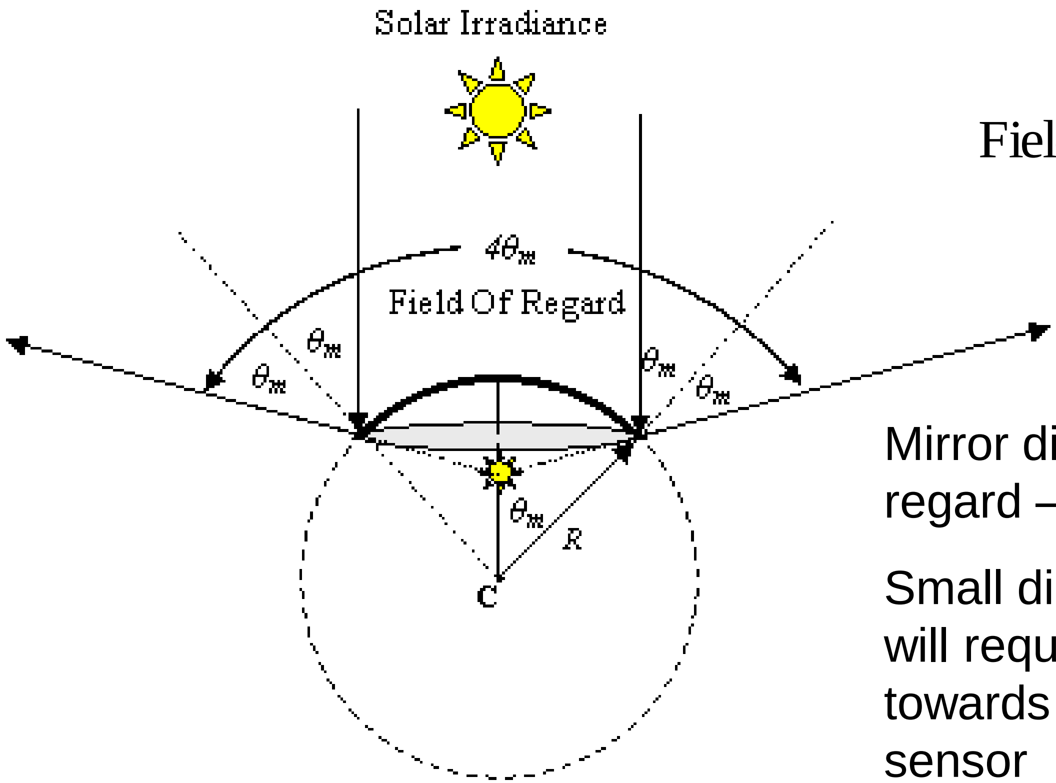
$$I_1 \propto R_1^2 \qquad I_1 \propto R_2^2 \qquad I_1 \propto R_3^2$$



$$R_1 \rangle R_2 \rangle R_3$$

Solid Angle Of Reflected Mirror Intensity (Field-Of-Regard)

Extent of the field-of-regard is determined by the diameter of the mirror (W)



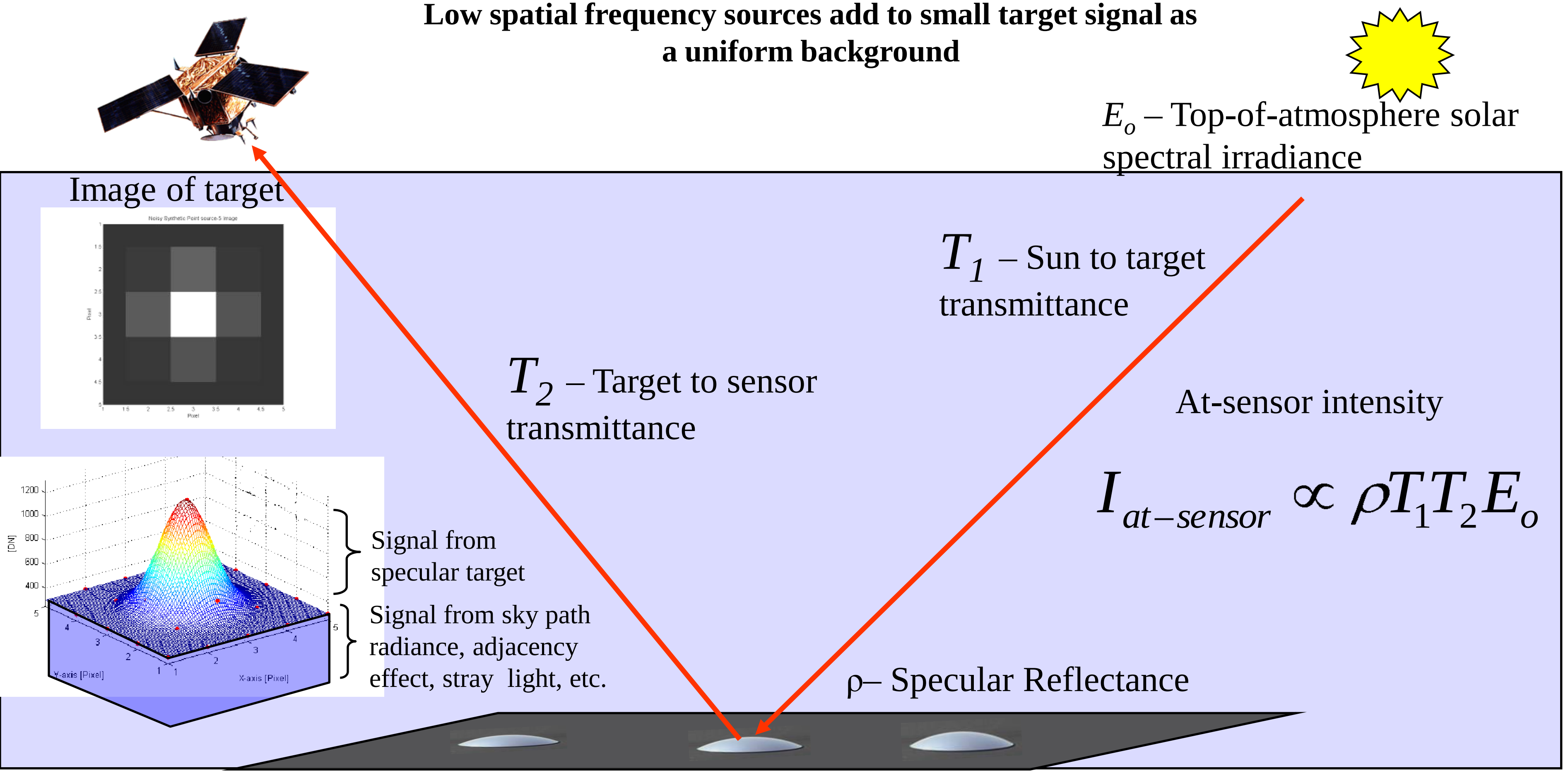
$$\text{Field-of-Regard} = 4\arcsin\left(\frac{W}{2R}\right)$$

Mirror diameter only affects the field of regard – not intensity

Small diameter mirrors can be used but will require alignment of the optical axis towards the midpoint between sun and sensor

Only Atmospheric Transmittance Drives Radiative Transfer Calculations

Low spatial frequency sources add to small target signal as a uniform background



Target signal is elevated above background (Surface background radiance, sky path radiance, adjacency effect, stray light, etc.) and separable – Background becomes a bias and is subtracted out based on image data alone

No need to "walk the site"

- Ground truth reflectance measurements are not needed!!
- No need for a field spectrometer (ASD)
- Mirror reflectance is measured in the laboratory (>5x more accurate than diffuse reflectance)
- Target reflectance uncertainty becomes negligible
- All measurements become instantaneous.
- Reflectance temporal variability issues go away when comparing data from different collects

SPARC Radiative Transfer Equation For Effective TOA Radiance

TOA Intensity

$$I(\lambda,\theta_r) = \tfrac{1}{4}\rho(\lambda,\theta_i)T_1(\lambda)T_2(\lambda)E_o(\lambda)R^2 \quad \text{watts/(sr micron)}$$

TOA Radiance/Mirror

$$L_{TOA}(\lambda,\theta_r) = \frac{\rho(\lambda,\theta_i)T_1(\lambda)T_2(\lambda)E_o(\lambda)}{\Omega_{IFOV}}\left(\frac{R}{2H}\right)^2 = \rho(\lambda,\theta_i)T_1(\lambda)T_2(\lambda)E_o(\lambda)\left(\frac{R}{2GSD}\right)^2$$

Watts/(m^2 sr micron)/mirror

$\rho(\lambda,\theta_i)$ = specular reflectance

$T_1(\lambda)$ = Sun to ground transmittance

$T_2(\lambda)$ = Ground to sensor transmittance

$E_o(\lambda)$ = Solar spectral constant

R = Mirror radius of curvature (m)

H = Sensor-to-mirror distance (m)

Ω_{IFOV} = Projected solid angle of single detector on the ground

GSD = Ground Sample Distance (m)

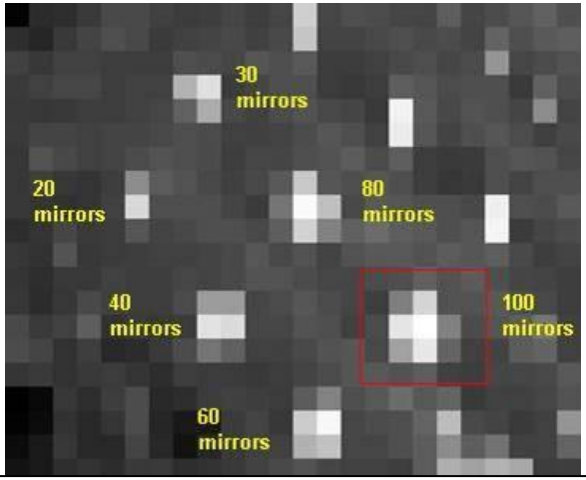
Uncertainty is dominated by the transmittance which is directly defined by the uncertainty in the calibration of the sunphotometer (all other terms are < 1%)

$$\sigma_{L_{TOA}}(\lambda) \approx 2\cdot\sigma_T(\lambda) \approx 2\cdot\sigma_{lo}(k)$$

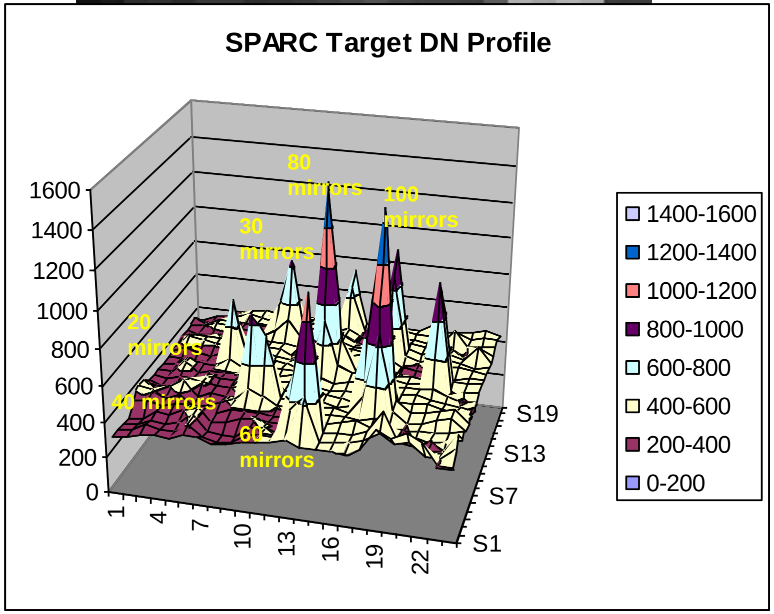
Where *lo(k)* is the TOA relative solar spectral response in sunphotometer band *k*

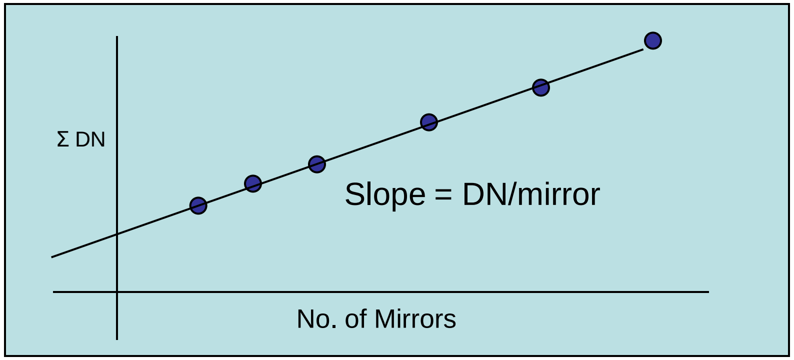
SPARC Target Image Analysis

- Simply measure the sensor response (Σ DN) of a set of SPARC targets having different effective radiance
- Processing consists of equalization of detector response but no resampling
- A square window is centered on each target and the DN values are summed. (Red box)
- Plot Σ DN vs. No. of mirrors to get DN/Mirror from the slope.
- If background is sufficiently uniform, in principle, no background analysis is necessary (Background affects the bias not the slope)



IKONOS Green Band Image





SPARC Based Absolute Gain Coefficient Calculation

$$CalCoef(\lambda) = \frac{DN/Mirror(\lambda)}{Radiance/Mirror(\lambda) \cdot Bandwidth(\lambda) \cdot EnsqEnergyCor} = DN/(Watts/m^2 sr)$$

$$Radiance/Mirror(\lambda) = \frac{\sum [L_{TOA}(\lambda, \theta_r) \cdot RSR(\lambda)]}{\sum RSR(\lambda)}$$ = Band integrated radiance [Watts/(m^2 sr)]/mirror

$DN/Mirror(\lambda) =$ slope of ΣDN vs. No. of mirrors measured from the SPARC target response profiles.

$Bandwidth(\lambda) =$ Bandwidth of spectral band λ (μm)

$EnsqEnergyCor =$ Estimated fraction of ensquared energy contained within the applied SPARC target response profile integration window (≈ 1).

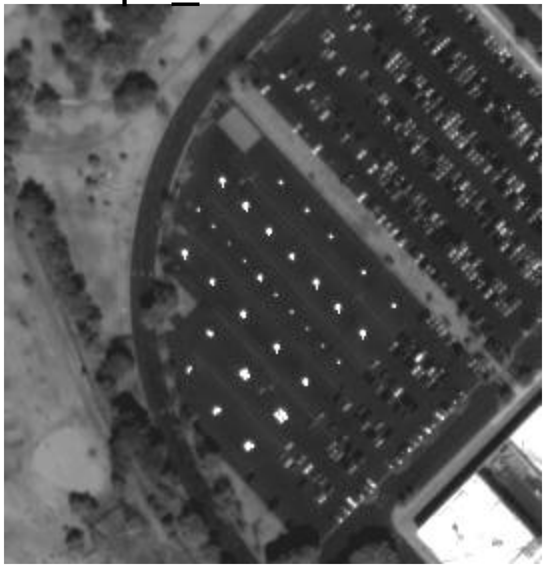
Corrects for energy lost in the wings of the PSF outside the DN/Mirror measurement window. Size of window depends on target separation practical for the ground site and background uniformity.

SPARC Method Applied to the Absolute Calibration of IKONOS

- On Sept 10, 2009, IKONOS images were collected of SPARC spatial and radiometric reflectors
- Site: Parking lot of Raytheon SAS Facility in El Segundo, CA.
- Two miles south of the LAX airport
- Elevation 35 m
- Three images were collected in a single overpass
- One recorded outside the field of regard to reveal detailed background levels (Limiting the width of the field-of-regard allows the scene to be viewed with the sun turned off!)
- For validation purposes number of targets is an overkill. In principle, only 4 to 6 SPARC targets are needed for radiometric calibration.

Sept 10, 2009 IKONOS Images

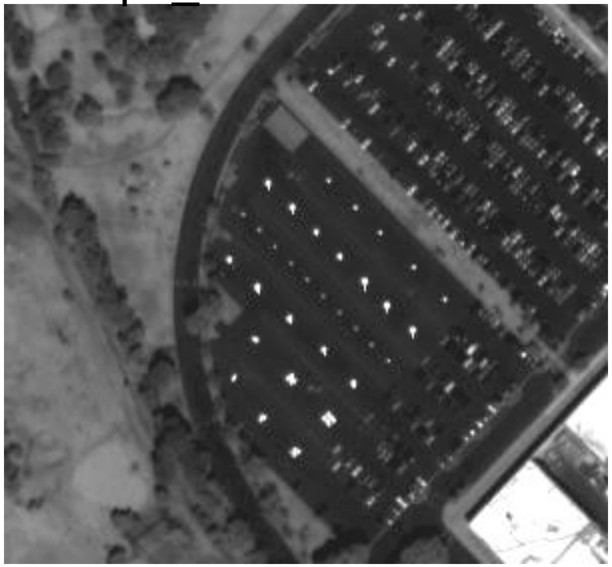
po_365282



Acquired Nominal GSD
- Pan Cross Scan: 0.91 meters
- Pan Along Scan: 0.87 meters
- MS Cross Scan: 3.64 meters
- MS Along Scan: 3.49 meters

Scan Azimuth: 180.01 degrees
Scan Direction: Reverse
Nominal Collection Azimuth: 66.7620 degrees
Nominal Collection Elevation: 70.34628 degrees
Sun Angle Azimuth: 146.0466 degrees
Sun Angle Elevation: 56.37735 degrees

po_365283



Acquired Nominal GSD
- Pan Cross Scan: 0.88 meters
- Pan Along Scan: 0.85 meters
- MS Cross Scan: 3.53 meters
- MS Along Scan: 3.41 meters

Scan Azimuth: 180.01 degrees
Scan Direction: Reverse
Nominal Collection Azimuth: 106.6828 degrees
Nominal Collection Elevation: 73.68076 degrees
Sun Angle Azimuth: 146.1832 degrees
Sun Angle Elevation: 56.41706 degrees

po_365284

Acquired Nominal GSD
- Pan Cross Scan: 0.92 meters
- Pan Along Scan: 0.99 meters
- MS Cross Scan: 3.68 meters
- MS Along Scan: 3.94 meters

Scan Azimuth: 0.01 degrees
Scan Direction: Forward
Nominal Collection Azimuth: 155.0008 degrees
Nominal Collection Elevation: 63.96876 degrees
Sun Angle Azimuth: 146.4022 degrees
Sun Angle Elevation: 56.48040 degrees

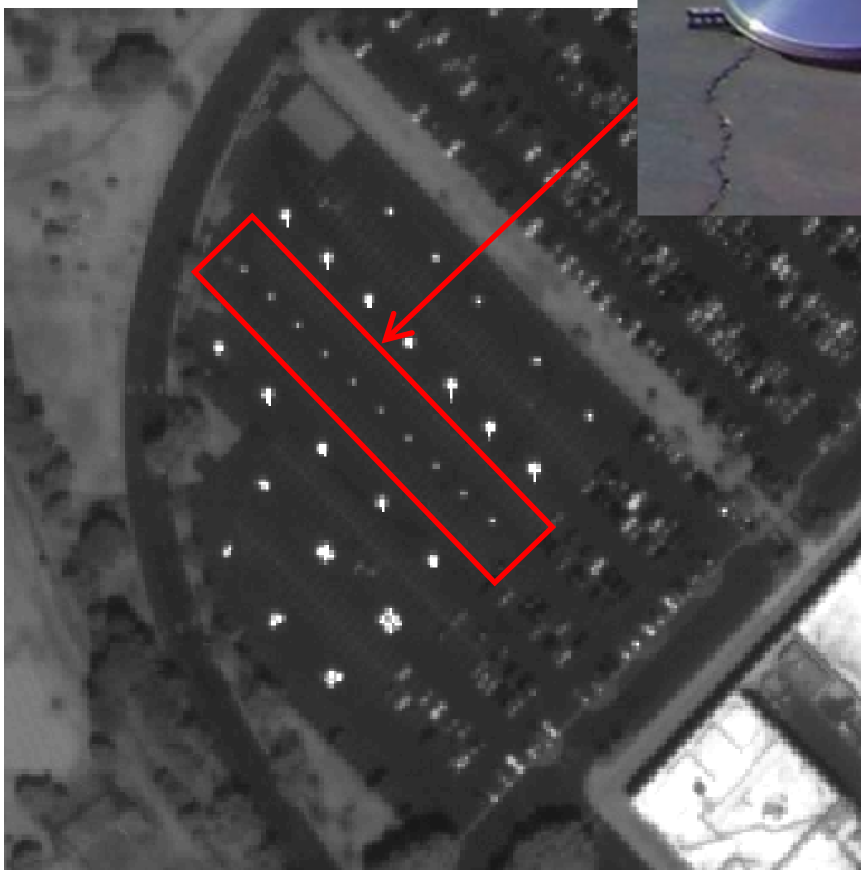
Images have limited processing – flat field response equalization but no resampling

Spatial Analysis

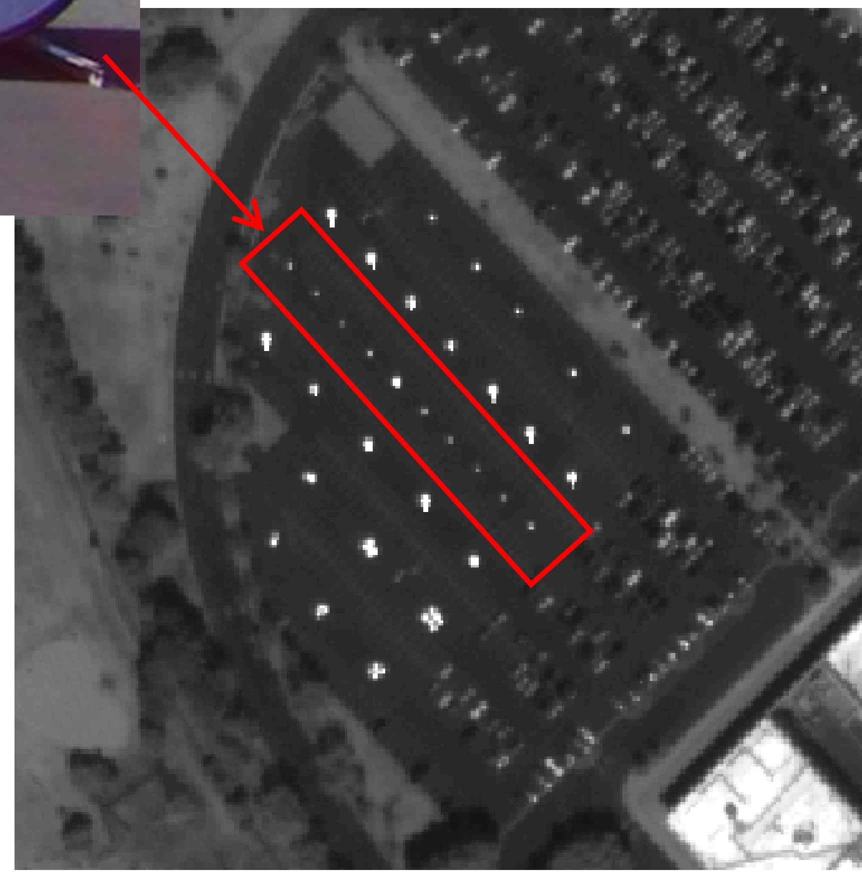
Mirror Array for Pan Band PSF FWHM measurements

20” diameter stainless steel convex mirror, R = 1.25 m

po_365282

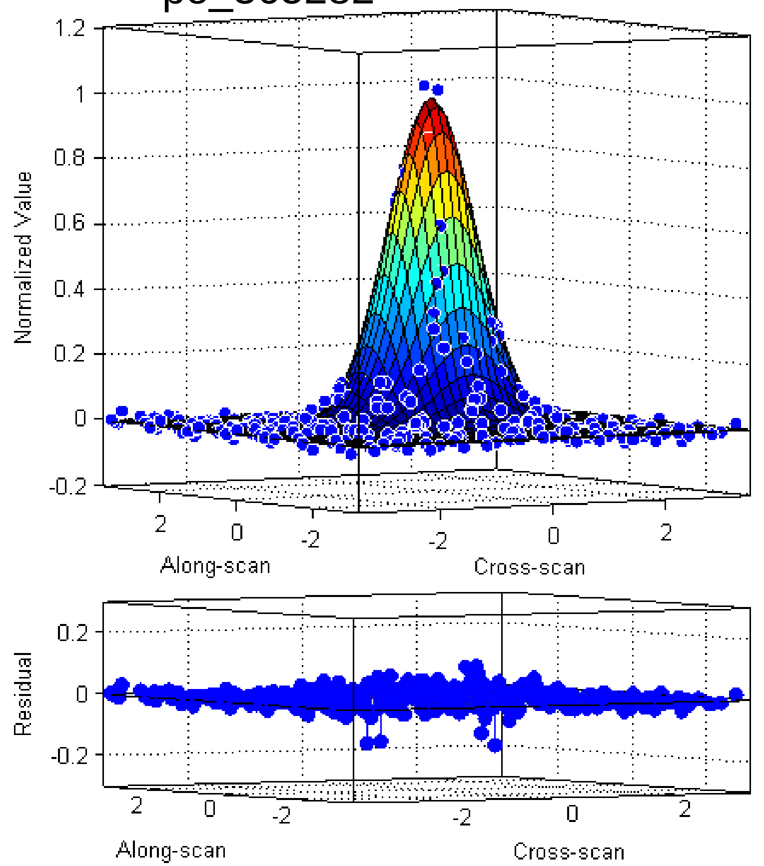


po_365283



Pan Band PSF FWHM Measurement

po_365282



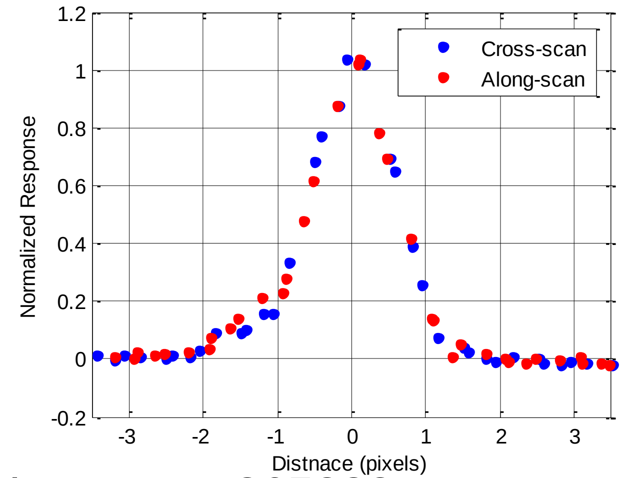


Image po_365282

Cross-scan FWHM	Along-scan FWHM
1.27 0.04 pixels	1.34 0.03 pixels

Image po_365283

Cross-scan FWHM	Along-scan FWHM
1.27 0.04 pixels	1.32 0.04 pixels

Multispectral detector pitch is 4x larger.

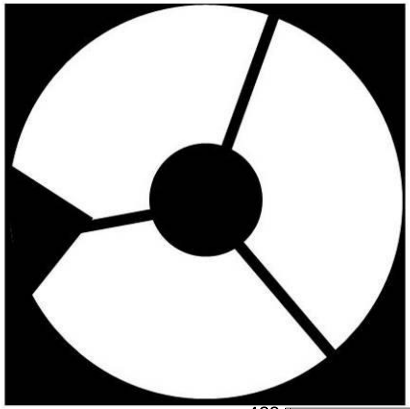
Implies multi-spectral FWHM ≈ 0.3 pixels (Band Dependent)

Confirms optical system can be modeled as roughly diffraction limited with nominal aberrations

Percent RMSE = 3.3%

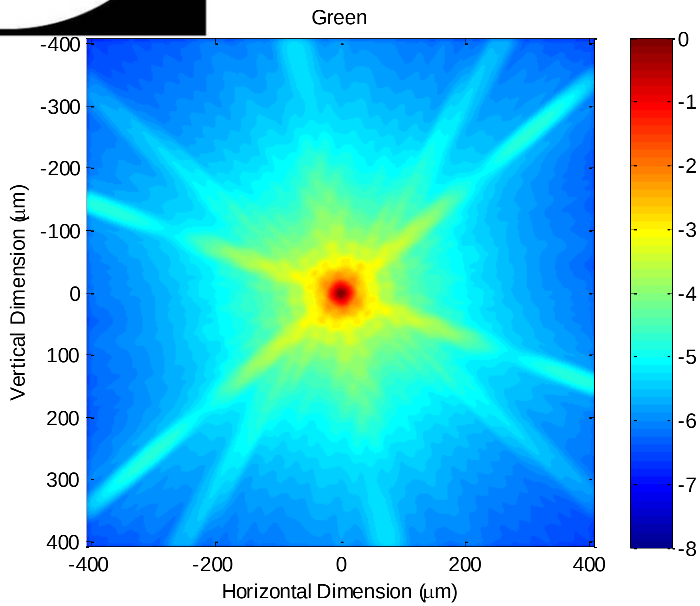
R^2 Coefficient of Determination = 0.96

Ensquared Energy Calculations

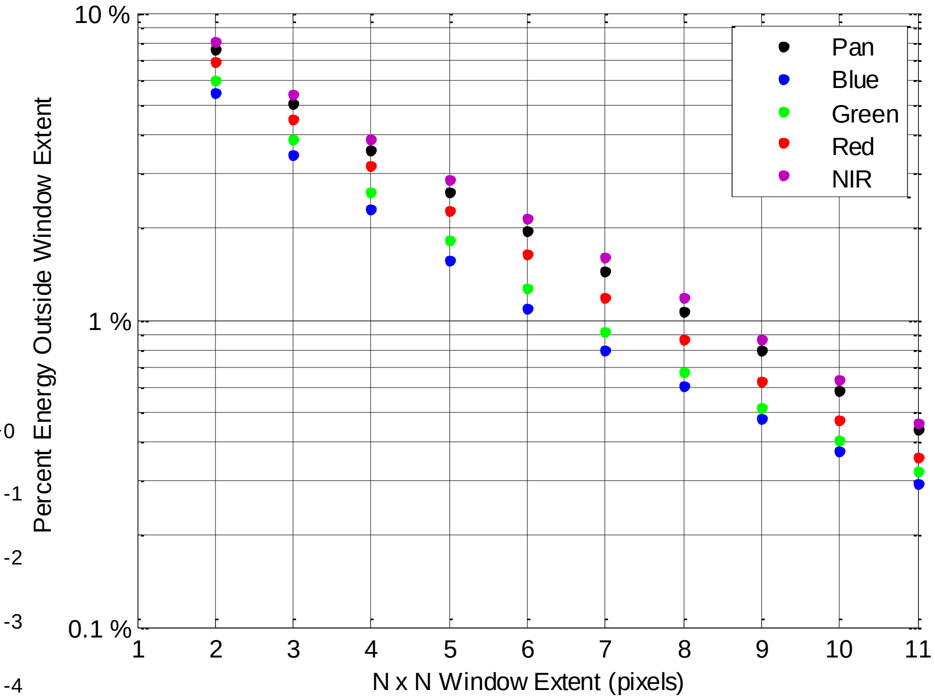


IKONOS Pupil Mask

Polychromatic PSF from pupil mask and preflight interferogram based model



Log Scale



Multispectral Band	Blue	Green	Red	NIR
EnsqEnergyCor (3x3 pixels)	0.968	0.962	0.958	0.948

Pixels are 48 µm square MSI band detector elements

Results are accurate to ~0.5 %

Image analysis of SPARC target background will be based on a 3 x 3 pixel window

(based on separation between targets in MS images)

Radiometric Analysis

- Atmospheric transmittance was measured with a shadowband radiometer.
- Aerosol extinction was derived and used to constrain MODTRAN model of atmospheric transmittance

MFRSR* Atmospheric Measurements for Sept. 10, 2009 IKONOS Overpass at 18:39 UTC.

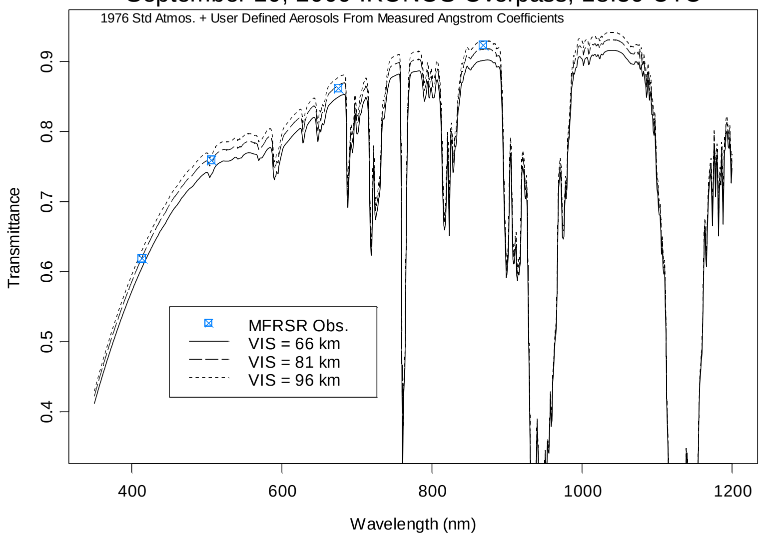
MFRSR Spectral Band Center (nm)	413.9	506.2	675.5	868.5
Transmittance Calibration Uncertainty (% 1 Sigma)	2.6	2.3	2.0	1.5
Sun to Ground Atmospheric Transmittance	0.619	0.759	0.861	0.923
Diffuse-to-Global Ratio	0.255	0.155	0.082	0.064

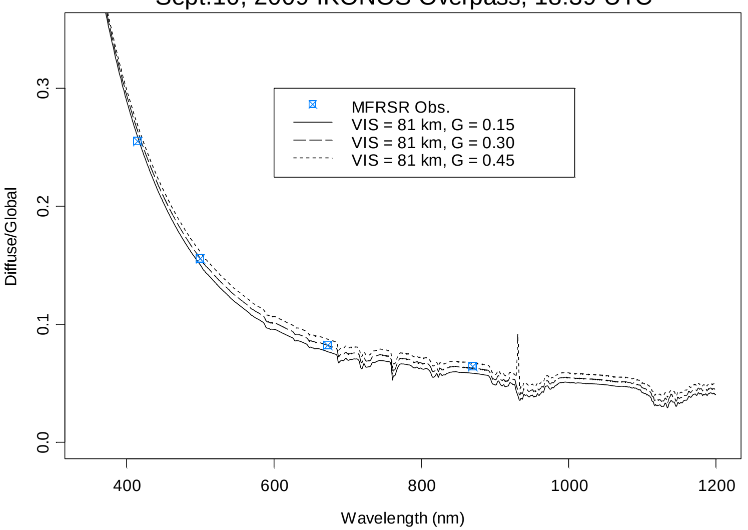
Uncertainty based on ~ 30 Langley plots recorded at the target site

***Multi-Filter Rotating Shadowband Radiometer**

Transmittance Spectrum Calculated with MODTRAN*

- Visibility parameter was adjusted to reproduce the observed transmittance and diffuse-to-global ratio at the time of the overpass





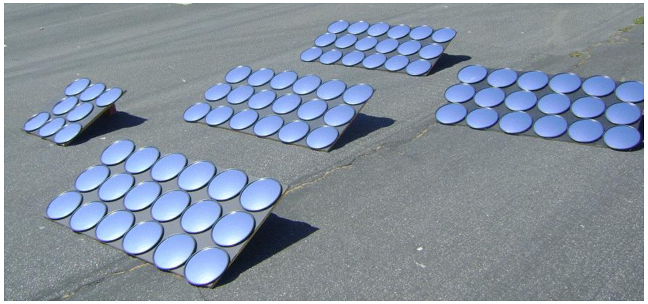
Minimum residuals were achieved (<2%) with VIS = 81 km

Agreement with diffuse-to-global ratio (relative measurement) provides independent confirmation that the sunphotometer was correctly calibrated.

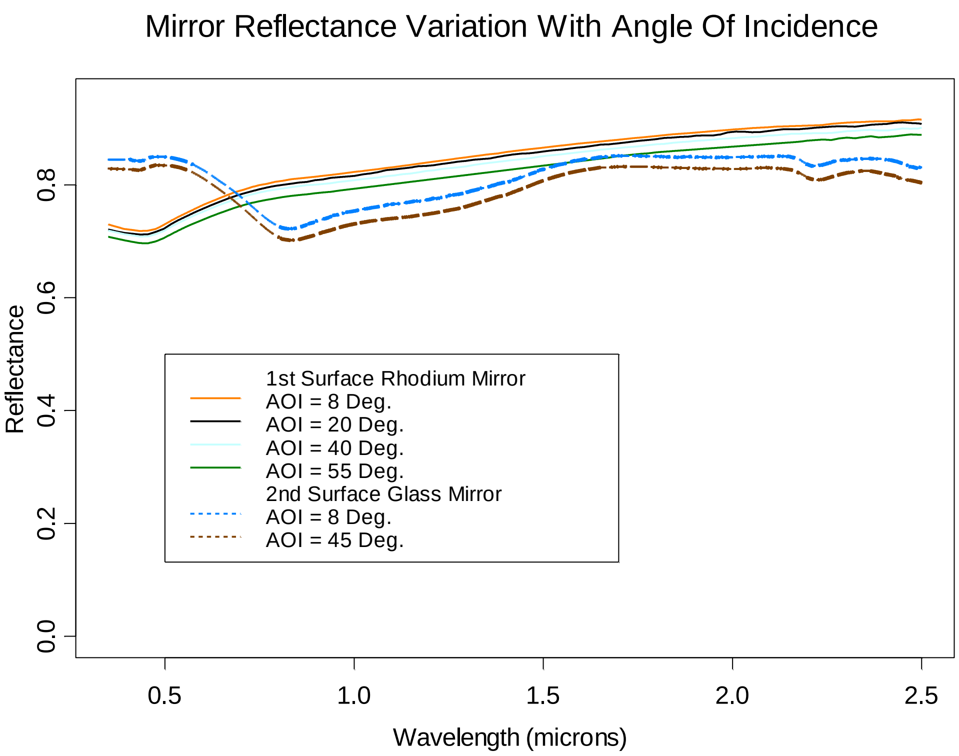
***MOD**erate resolution atmospheric **TRAN**smission

Mirror Reflectance Spectrum: Measured with a Laboratory Reflectometer

- Mirrors deployed on asphalt parking lot
- 2nd surface aluminized glass mirrors (D.O.T. approved truck mirrors with R = 18 inches)



- Reflection is high, spectrally flat and varies slightly with angle of incidence (AOI)

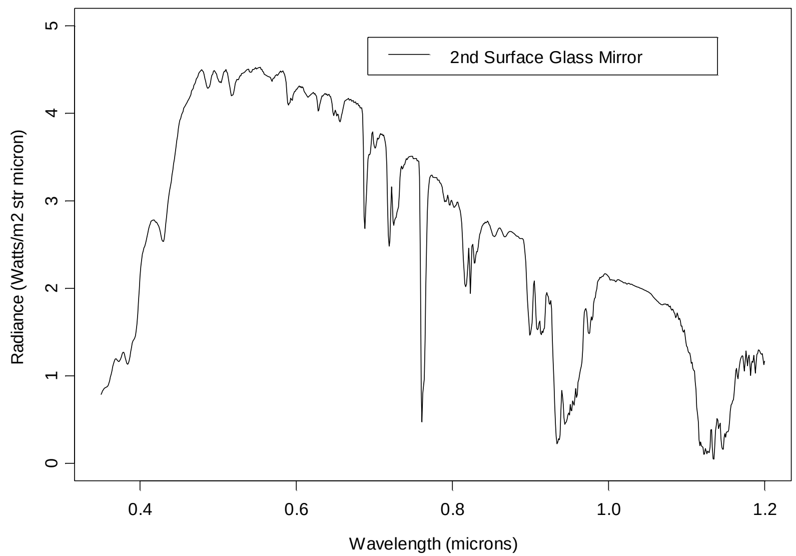


- Reflectance knowledge accuracy ~0.25% VNIR and ~0.5% SWIR (1 sigma)
- Slight variation corrected by interpolation based on AOI for each collect

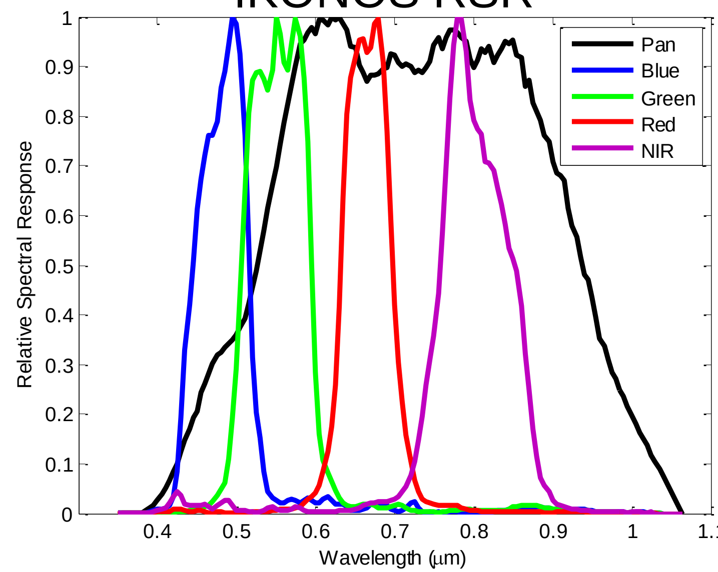
TOA Radiance Spectrum Calculated

Apply the SPARC radiative transfer equation , $L_{TOA}(\lambda,\theta_r)=\rho(\lambda,\theta_r)T_1(\lambda)T_2(\lambda)E_o(\lambda)\left(\frac{R}{2GSD}\right)^2$, and convolve the radiance (L_{TOA}) spectrum with the sensor's relative spectral response (RSR)

Top-Of-Atmosphere Effective Radiance Spectrum For A Single Mirror



IKONOS RSR

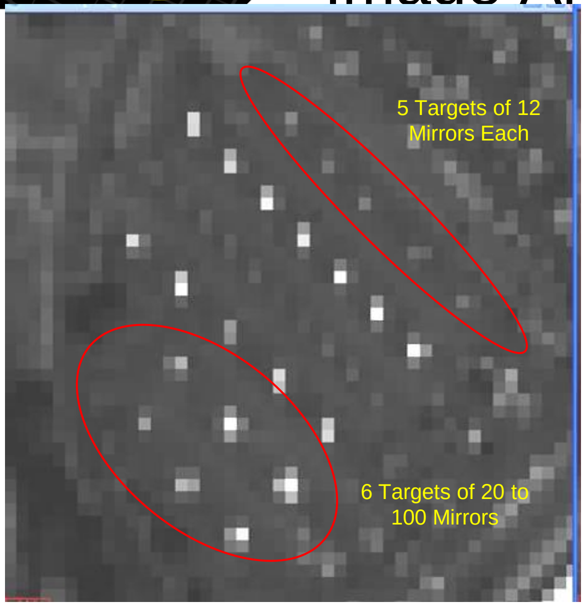


	IKONOS TOA Band Predicted Radiance [Watts/(m2 sr micron)]			
Image/Mirror	Blue	Green	Red	NIR
po_365282 /Glass	4.128	4.345	3.919	2.817
po_365283 /Glass	4.104	4.327	3.908	2.811

Provides in-band radiance/mirror

Variation mainly from sensor-to-ground transmittance differences between images

Image Analysis: Measurement of Target Signal



$$\text{Target } \Sigma\text{DN} = \sum_{n=1}^{9} \left[DN(n) - \overline{DN}_{background} \right]$$

- Total Target DN summed over 3x3 window (green box).
- $\overline{DN}_{background}$ obtained from perimeter pixel average.

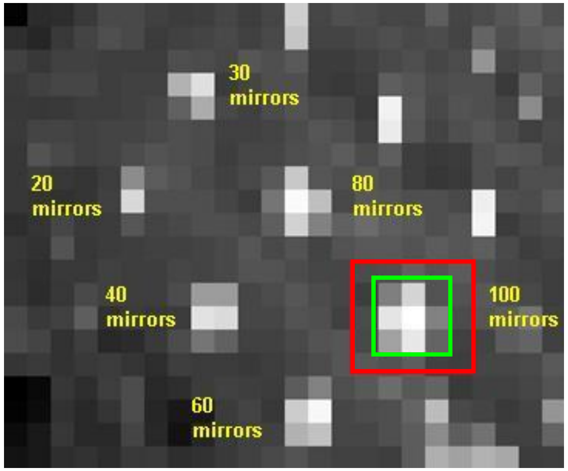
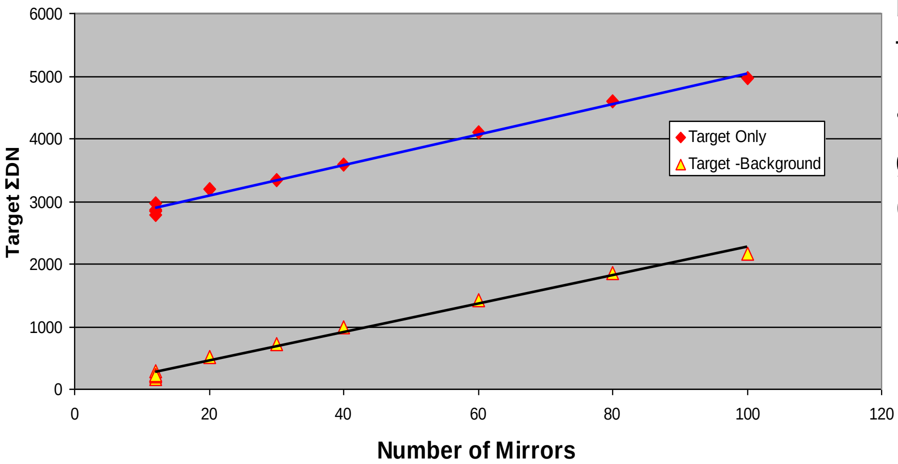


Image po_365282 Red Band DN/Mirror



- Limited size of target area created the need for background correction (better site design would make this step unnecessary).
- Background subtraction corrects for net uniformity gradients that would introduce systematic error in slope (Example for IKONOS red band image).

Red Band Image po_365282	Slope: DN/Mirror	R^2	RMSE Residuals (DN)
Target Only	24.4	0.9922	67
Target - Background	22.8	0.9917	65
% Change	6.6%		

6.6 % Correction

Image Analysis: Measurement of DN/Mirror

Spectral Band	Slope: DN/Mirror	R^2
Blue	17.9	0.9898
Green	25.2	0.9972
Red	22.8	0.9917
NIR	19.8	0.9965

Slope provides the measurement of the IKONOS band responsivity

Spectral Band	Slope: DN/Mirror	R^2
Blue	17.2	0.9963
Green	24.8	0.9886
Red	23.4	0.9904
NIR	18.2	0.9913

IKONOS Absolute Gain Results Using the SPARC Method (Preliminary*)

$$CalCoef\,(\lambda) = \frac{DN / Mirror(\lambda)}{Radiance / Mirror(\lambda) \cdot Bandwidth(\lambda) \cdot EnsqEnergyCor} = DN / (Watts / m^2 sr)$$

SPARC Method Results	**Blue**	**Green**	**Red**	**NIR**
po_356282 / Glass Mirrors	**63.1**	**68.1**	**92.6**	**77.8**
po_365283 / Glass Mirrors	**60.9**	**67.1**	**95.4**	**71.6**
Average	**62**	**67.6**	**94**	**74.7**
Comparison to Calibration Coefficients Provided By GeoEye.				
NASA Ground Calibration (JACIE 2001)	**63.3**	**64.9**	**84**	**74.6**
% difference	**2.05**	**4.16**	**11.9**	**0.13**
Stellar Calibration (Bowen 2001)	**57.5**	**58**	**70.8**	**58.9**
% difference	**7.83**	**16.55**	**32.77**	**26.83**

Preliminary results from the SPARC method are most consistent with reflectance-based calibration made by the NASA/JACIE team

Bandwidth from publication “IKONOS Esun Calculations” at www.geoeye.com

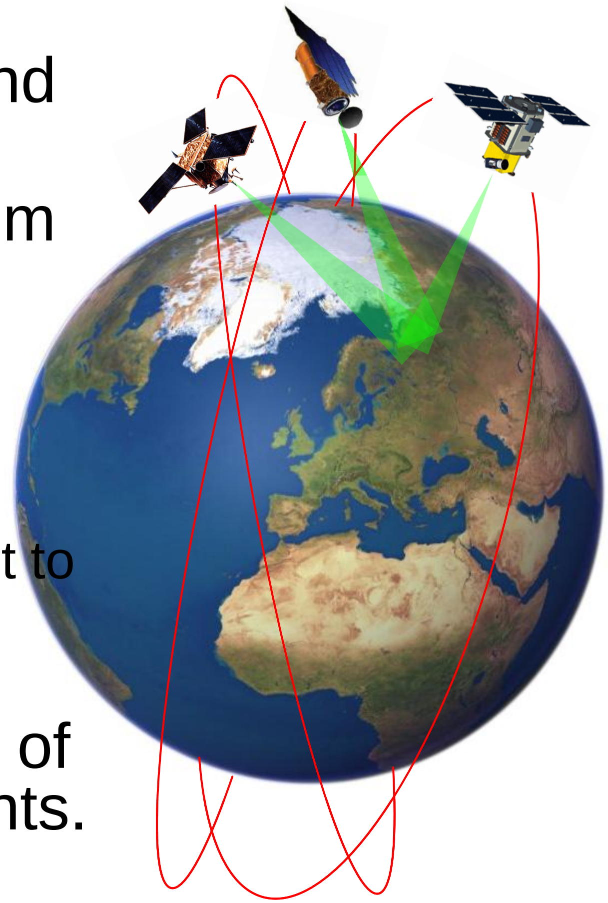
*Other 2009 collects are being processed

Conclusion

- Initial results indicate that the SPARC vicarious method provides absolute calibration performance consistent with the reflectance-based vicarious calibration method.
- The SPARC method can provide simultaneous spatial and radiometric calibration.
- The SPARC method achieves absolute vicarious calibration at a significantly lower cost and effort than the reflectance-based method.
- The SPARC methodology eliminates all atmospheric effects except for transmittance in the calibration process. Potential to achieve better accuracy than reflectance-based method.
- Currently, the largest uncertainty source in deriving sensor gain comes from net gradients in target background affecting the DN/mirror measurements (Improved site design can fix this).
- Can be set up at any remote sensing study site (Does not need to be done at a high desert playa location. Validation was accomplished in a major urban setting at sea level)

Future

- Potential to make <5% absolute accuracy routine with a hand held sunphotometer and a few SPARC panels.
- Mountain top deployment of SPARC system could achieve <2% absolute accuracy.
- Application to larger footprint sensors with automated pointable SPARC Panels.
- Consistent solar calibration across VNIR, SWIR, and MWIR sensors (SPARC works out to 6 microns).
- Accurate polarimetric calibration. Simply replace measured natural light reflectance of mirrors with **s** and **p** reflectance components.
- Improved cross-platform calibration of a sensor constellation. (view geometry/temporal reflectance stability with reduced atmospheric effects avoid the need for simultaneous collects)



- Acknowledgement: We would like to thank GeoEye, Inc., Thornton, Colorado, for their collaboration in providing the IKONOS imagery and specifically Martin Taylor for his fantastic job in coordinating satellite tasking with ground operations.

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